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LIFE-CYCLE ASSESSMENT AND URBAN SUSTAINABILITY

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PREFACE

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ABSTRACT

Sustainable community assessment has become increasingly important for regions, counties, and cities as land use strategies and other local policies are developed to reduce fossil fuel consumption and its impacts. New quantitative methodologies are needed as new policies are developed and implemented at regional and local scales to assess their system-wide impacts so that energy-related problems in one location are not traded for problems in another.

Urban metabolism is a comprehensive systems approach for sustainable city assessment that has been applied to many cities throughout the world. Urban metabolism measures the total energy, resources, and waste products that flow into and out of a city or metropolitan region. Changes in flows are evaluated over time to determine if cities are shifting consumption patterns. Interactions between transportation, land use, water, waste and energy of the urban region can then be identified and quantified. This analysis enables decision-makers to better understand the causes and effects of increased energy consumption and determine how to target reduction efforts. However, urban metabolism does not assess the life-cycle impacts of these flows, including the energy, economic, and environmental costs that occur beyond the region's boundaries.

Life-cycle assessment is the cradle-to-grave analysis of the environmental, social, and economic impacts associated with a product, process, or service. This project assessed how the life-cycle assessment method could be integrated with urban metabolism to: 1) develop comprehensive energy and environmental inventories for cities and metropolitan regions; 2) provide metrics that connect regional and local decisions to environmental and human health damages; and 3) evaluate the effects of waste streams outside the urban boundaries. The urban metabolism framework provided a foundation for understanding city resource use and waste production. The integration of life-cycle assessment principles will provide a more rigorous environmental valuation with more focused recommendations for sustainable community policy.

Keywords: California Energy Commission, sustainable communities; life-cycle assessment; urban metabolism; city; policy

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EXECUTIVE SUMMARY

Introduction

Sustainable community assessment has become increasingly important for regions, counties, and cities as land use strategies and other local policies are developed to reduce fossil fuel consumption and its environmental and human health impacts. New quantitative methodologies are needed as new policies are developed and implemented at regional and local scales to assess their system-wide impacts so that energy-related problems in one sector, city, or region are not traded for problems in another.

Evaluating large metropolitan areas with many interrelated technical and socioeconomic processes requires well-developed approaches. Life-cycle assessment has emerged as the preeminent approach for evaluating complex sectors and urban metabolism has evolved to analyze city processes. These two approaches have been developed for many decades and acknowledge the methodological challenges and uncertainty in systems-oriented analysis.

Project Purpose

The goal of this project was to analyze methods for combining life-cycle assessment with urban metabolism. Urban metabolism is a comprehensive systems approach for sustainable city assessment that has been applied to many cities throughout the world for nearly five decades.

Project Results

Urban metabolism measures the total energy, resources, and waste products that flow into and out of a city or metropolitan region. Changes in flows are evaluated over time to determine if cities are shifting consumption patterns (e.g., consuming more energy per capita or economic output). Interactions between transportation, land use, water, waste and energy of the urban region can be identified and quantified from this analysis. The analysis enables decision-makers to better understand the causes and effects of increased energy consumption and determine how best to target reduction efforts. However, urban metabolism does not assess the life-cycle impacts of these flows, including the energy, economic, and environmental costs that occur beyond the city or region's geographical or jurisdictional boundaries.

Life-cycle assessment is the cradle-to-grave analysis of the environmental, social, and economic impacts associated with a product, process, service, or sector. Life-cycle assessment has become synonymous with the study of environmental impacts such as energy consumption, greenhouse gas emissions, criteria pollutants, and toxic and carcinogenic releases and it can also inventory other social and economic indicators like the availability of labor and money. In addition, life-cycle assessment offers a methodology for evaluating the effects of waste streams. The urban metabolism approach stops evaluating the effects of waste streams once they leave the urban area. The processing of waste is by itself a complicated system that can transform city waste products into new materials or return those waste products to the environment from which they were processed. The ultimate fate of waste outputs can tip the environmental balance of upstream processes and should therefore be included in sustainable community assessment. Life-cycle assessment offers a framework for evaluating urban outputs from their disposal to their potential reprocessing or return to the environment.

The authors concluded that supplementing the life-cycle assessment approach with the urban metabolism approach could provide a more comprehensive framework for assessing the sustainability of communities. Ultimately, the use of the urban metabolism and life-cycle assessment approaches in sustainable community assessment will help: 1) develop comprehensive energy and environmental inventories for cities and metropolitan regions; 2) provide metrics that connect regional and local decisions to environmental and human health damages; and 3) evaluate the effects of waste streams outside the urban boundaries.

Project Benefits

The information in this report can be used to develop sustainable communities with less reliance on fossil fuels for energy, which will reduce greenhouse gas emissions that contribute to climate change, as well as other emissions that have negative impacts on the environment and human health.

CHAPTER 1: Background

As populations shift toward greater urban habitation, it becomes increasingly important to understand how resources enter, are processed, and exit cities. Appropriate balance between urban areas and their supply chains is necessary to ensure sustainable resource consumption and avoidance of impact displacement. The understanding of how resource inputs and waste accumulate in cities is critical in sustainable development considerations (Kennedy 2007). Cities that consume more materials and energy and produce more waste than the ability of their hinterlands to process can be considered unsustainable (Goodland 1996). Furthermore, how cities transform inputs into useful work, processes, goods, services, and wastes impacts populations both inside and out of the urban area (Chester 2010). An understanding of how cities metabolize resource inputs into desired products with zero or minimal environmental and human health impacts is critical in the identification and development of policy options. A systems-oriented environmental framework that captures direct, indirect, and supply chain processes associated with resource use or decision is necessary for comprehensively evaluating the complex urban system.

The life-cycle assessment (LCA) framework offers a methodological foundation for evaluating complex systems and can complement the urban metabolism approach for sustainable city evaluation. LCA describes the cradle-to-cradle assessment of a process or larger system including direct, indirect, and supply chain effects. While LCA has become synonymous with environmental assessment, its use can be broadly applied to many technical or non-technical indicators of interest. Life-cycle environmental inventories have been performed on energy consumption and emissions of greenhouse gases (GHG) and criteria air pollutants (CAP) of large systems (we acknowledge that CAPs include ozone and these studies typically evaluate VOCs instead, which including NO_X are the precursors to ozone formation) (Chester 2010, Chester 2009a, Chester 2009b, Stokes 2009 Facanha 2007, Facanha 2006, Guggemos 2006). While these environmental indicators are common in LCAs, hazardous wastes, toxic releases, carcinogenic releases, and many others can be evaluated. Life-cycle cost assessment (LCCA) is the economic arm of LCA designed to evaluate system-wide costs and benefits. Material flow analysis is directly related to LCA and can be used to track the supply chain effects of the production of goods or processes (Bouman 2000). Tracking the availability of autochthonous resources and labor is also possible. Pfister (2009) creates an LCA method for evaluating freshwater consumption using global cotton production as a case study. EIO-LCA (2010), an LCA modeling program, captures total labor requirements (reported as the total number of employees needed throughout the supply chain) for any process. The fundamental LCA principles are not specified for any particular indicator (e.g., energy, emissions, costs) but are generalized for any item that can be specified as an input or output to processes in a system. This makes the framework particularly valuable when evaluating sustainable community assessment.

Urban metabolism has become the primary methodology for sustainable city assessment. The technique typically evaluates energy, material, water, and nutrient inputs and outputs through urban regions (where outputs also include waste in various forms) (Kennedy 2007). Originally developed by Wolman (1965), urban metabolism is a methodology for evaluating the stocks of inputs and outputs through a city and the processes that transform them within. When evaluated over time, changes in flows are used to determine if cities are shifting consumption patterns (e.g., consuming more energy per person) and inferences are drawn as to the significance. Sustainability in the context of the ability of the city's hinterlands to provide inputs and process outputs, and the impacts of how metabolic processes use inputs and produce outputs, are discussed (e.g., accumulation of nutrients and toxic chemicals, urban heat island effects). Urban metabolism does not call for the inclusion of supply chain upstream effects or quantitative impact assessment for the local environment or to human health.

With increasing interest in urban sustainability in California given recent climate and urban planning legislation, new approaches should be developed to comprehensively evaluate the impacts of policy on environmental and human health well-being. Combining the principles of LCA with urban metabolism provides an improved methodology for understanding the impacts from processes in cities. The LCA framework starts with the inventorying of processes within a system and ends with impact assessment. Urban metabolism is equivalent to the first step in the inventorying process but should be supplemented with indirect and supply chain processes. Furthermore, impact assessment should be instituted in urban metabolism studies to evaluate environmental and human health effects of city and supply chain processes beyond qualitative assessments of changes in flows. The LCA framework has been clearly defined and can be used with urban metabolism in developing more comprehensive sustainability assessments of cities.

CHAPTER 2:
Systems-Oriented Approaches

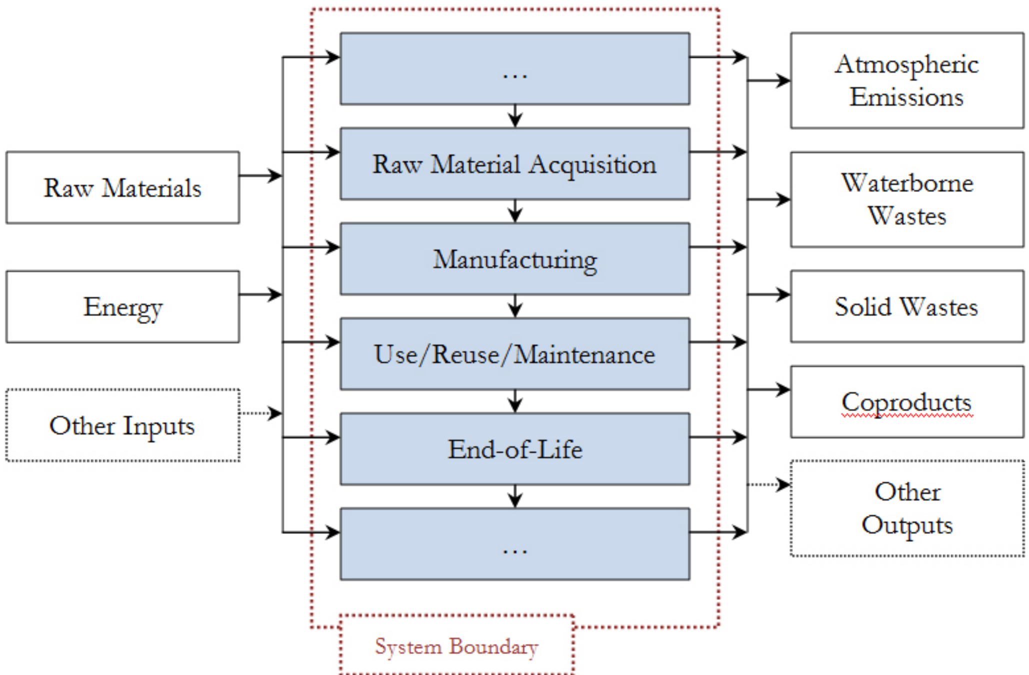
Evaluating large networks with many interrelated technical and socioeconomic processes requires well-developed approaches. LCA has emerged as the preeminent framework for evaluating complex systems, and urban metabolism has evolved to analyze city processes. These two frameworks have been developed for many decades and acknowledge the methodological challenges and uncertainty in systems-oriented analysis.

2.1 The Life-Cycle Assessment Framework

LCA is the cradle-to-cradle evaluation of processes and systems incorporating direct, indirect, and supply chain effects. The term *life-cycle assessment* includes inventorying (LCI: assessing the flows of resource inputs and emissions outputs), impact assessment (LCIA: identifying the impacts of the resource use and emissions, e.g., material depletion or human health effects), and interpretation (re-evaluation of the LCI and LCIA to reduce uncertainty and impacts by evaluating critical process parameters) phases. A comprehensive LCA should include all of these phases. The International Organization for Standardization (ISO) has formalized the definition of LCA in its 14040 series specifying that 1) goal and scope definition, 2) inventory analysis, 3) impact assessment, and 4) interpretation should be included. There are some cases, however, where inventory analysis and impact assessment can be considered the same (e.g., energy consumption and GHG emissions, although O'Hare (2009) points out that in the case of climate change society is ultimately concerned with heating). And several studies distinguish themselves as LCIs (and not full LCAs) by quantifying emissions from activities but stopping before impact assessment acknowledging the complexities of modeling environmental and human health impacts [Chester 2009a, Facanha 2007, Facanha 2006].

The LCA framework includes considerations for system boundary selection and functional units and can evaluate direct, indirect, and supply chain processes for the system of interest. The direct component is the immediate process of interest. For example, when performing an LCA of an automobile, the direct process of interest would be operating a car that requires gasoline as an energy input and produces emissions in combustion [Chester 2009a]. Indirect processes are the processes that must exist for the direct process to function. In order for an automobile to operate, it must be manufactured and maintained, roads must be constructed, and petroleum refined. While it is common for an LCA to draw a system boundary around direct and indirect components, it is important to consider supply chain effects. The supply chain is all upstream activities throughout an economy (or global network) that in some part exist to support the direct and indirect components. Roadway construction requires aggregate mining that is performed by machinery combusting diesel fuel. And steel must be produced for petroleum refining plant construction. Several LCAs show that the majority of some emissions (particularly CAP) occur in the supply chain and not necessarily in the direct or indirect processes of immediate interest [Chester 2009a, Facanha 2007, Facanha 2006]. The system boundary selection is the most critical underlying assumption of the analysis because if not chosen properly, can exclude components that if included would change the conclusions of the assessment. Figure 1 illustrates a generic system of interest with inputs (raw materials and energy), outputs (atmospheric emissions, waterborne wastes, solid wastes, and coproducts) as well as a system boundary. The life-cycle components included (raw material acquisition, manufacturing, use/reuse/maintenance, and waste management) are but a few that could potentially be considered. For example, Chester (2009a) includes 79 life-cycle components in the assessment of several passenger transportation modes. Additionally, the inputs and outputs shown in Figure 1 represent only a handful of the almost limitless options for LCA systems analysis. All inputs and outputs, however, must be normalized for useful conclusions.

Figure 1: Generic LCA System Boundary



Functional units allow for normalization of LCA results across multiple components, time frames, and geography. When evaluating emissions from the automobile life cycle, it is necessary to incorporate both vehicle manufacturing as well as "tailpipe" operation factors [Chester 2009a]. While emissions from vehicle manufacturing results are typically first evaluated as a one-time puff, vehicle tailpipe factors are usually considered during operation, or per unit distance traveled during the lifetime of the vehicle. In order to combine the two life-cycle components in a meaningful comparison, the functional unit must be established, and the results normalized to that metric. For example, Chester (2009a) normalizes the LCI emissions of different transportation modes per vehicle and passenger-mile-traveled (further referred to as VMT and PMT). With this functional unit, the emissions from manufacturing a car would be divided by the car's expected lifetime VMT and PMT (acknowledging that the impact of the emissions from the two life-cycle components must be evaluated independently with temporal and geographic considerations). The establishment of the functional unit is a necessary first-step in any LCA and does not have to be limited to a single metric. It is the foundation of assessing quantitative results across an array of direct, indirect, and supply chain components.

The inclusion of direct, indirect, and supply chain components that are triggered through the activity of interest can be evaluated through several LCA approaches. Process and economic input-output (EIO) are the two primary approaches for performing an LCA and can be used in conjunction [Hendrickson 2006]. The Society of Environmental Toxicology and Chemistry and the United States Environmental Protection Agency have led the standardization of process-based LCA in the U.S. [EPA 1993, SETAC 1993]. Process-based LCA is the brute-force approach of evaluating a large system and its interdependent components. Once the system boundary has been established, the direct component of interest is evaluated considering the inputs and outputs of interest. Next, all subprocesses to this first process are then evaluated moving up the supply chain. In LCA, it is often the case that indirect processes exist to support the processes of interest (e.g., some fraction of total salt production exists, requiring resource inputs and producing emission outputs, to de-ice roadways, and could therefore be included in the LCA of an automobile). Once subprocesses have been evaluated, the next level of sub-subprocesses would be considered. For each step, data is gathered and component inventories are determined, and when normalized to the functional unit, produce the LCI. While process-based LCA is the preferred approach to use the most representative data and evaluate system-specific components, it requires such intense data and resource requirements that evaluating the entire supply chain is impossible [Hendrickson 2006]. For process-based LCA, proper establishment of the system boundary is critical in creating a comprehensive assessment that does not miss any game-changing components but also creates a reasonable work scope for the practitioner. (The scoping challenges for biofuel environmental assessment highlight the importance of appropriate system boundary selection as illustrated by Farrell 2006 and Searchinger 2008.) Acknowledging these limitations, the EIO approach was developed to complement the resource constraints of process-based LCA [Hendrickson 1998]. EIO models show supply chain interactions among all sectors of an economy and when joined with environmental data can be used for LCA [Leontief 1970]. The EIO-LCA approach evaluates the resource inputs and emissions outputs associated with economic activity in every sector of the economy. When evaluating automobile manufacturing, some amount of steel was purchased to produce the car, and going up the supply chain shows that in producing that steel electricity was produced, first requiring coal [Hendrickson 2006]. These interdependencies go on throughout the entire supply chain and mathematical approaches for estimating them have been established [Hendrickson 1998]. Hybrid LCA is the combination of process and EIO-based LCA to reduce data and resource constraints in modeling while capturing the entire supply chain. Hybrid LCA calls for the use of process-based LCA through the first few tiers of processes and sub-processes to capture major life-cycle components with high resolution data. When sub-processes align with economic sectors, the EIO approach is then used to evaluate up the supply chain. The hybrid LCA approach also operates with some methodological uncertainty that should be acknowledged and addressed. However, this approach has shown to be a good alternative to the process-based approach offering more comprehensive system wide assessment [Chester 2010, Stokes 2009, Chester 2009a, Facanha 2007, Facanha 2006, Guggemos 2006].

2.2 The Urban Metabolism Framework

Urban metabolism is an input-output material or energy assessment of cities. The framework was originally conceived by Wolman (1965) for a hypothetical city evaluated with U.S. data and has evolved to consider both technical and socioeconomic effects of how cities use resources and dispose of waste [Kennedy 2007]. There have been many urban metabolism studies of cities worldwide since Wolman (1965) and they typically focus on energy, water, materials, nutrients, and waste [Kennedy 2007]. More recently, several urban metabolism studies have included air emissions [Kennedy 2009a, Kennedy 2009b, Warren-Rhodes 2001, Decker 2000,].

Similar to LCA, urban metabolism relies principally on the law of conservation of energy, that energy or matter coming into a city must be equal to what is inside the city (accumulated) plus what is output (which includes forms of waste and emissions), as shown in Figure 2.

Figure 2: Fundamental Energy and Mass Balance Concept for LCA and Urban Metabolism

Using this concept, many city urban metabolisms have been created knowing that energy, water, materials, and nutrients that enter a city must be in the city scope or have exited (potentially in a new form) [Barles 2009, Barles 2007, Huang 2003, Huang 1998, Duvigneaud 1977, Færge 2001, Forkes 2007, Niza 2009, Ngo 2008, Sahely 2001, Svidén 2001, Tarr 2002, Warren-Rhodes 2001, Zhang 2009, Zhang 2007].

The urban metabolism framework is still developing and does not have consistent metrics for evaluating resource consumption or waste outputs. Additionally, two schools of thought have emerged on how to evaluate these flows. The first group evaluates mass fluxes in metrics that are generally more useful to decision-makers and planners. [See Kennedy (2007) for a comprehensive summary of literature.] The second group chooses to represent flows in a common functional unit of energy equivalents, largely based on the work of Odum (1983) [Zhang 2009, Huang 2003, Huang 1998]. The understanding of how resources enter cities, accumulate, and exit as waste can be considered an indicator of sustainable growth and development [Decker 2000].

While urban metabolism mass and energy flow metrics have been considered reasonable indicators of city sustainability, the inclusion of more complex socioeconomic conditions is important. Considering a city that consumes more resources or generates more waste than its hinterlands can produce or process [Goodland 1996] is a good start, but the quality of resource use from both technical and socioeconomic perspectives is also important. Consumption of energy, water, materials, and nutrients per capita is most useful when combined with growth indicators (e.g., Gross Domestic Product, education) to measure how effective these resources are at performing work and achieving effective growth, and improving quality of living. Furthermore, the acknowledgement of waste as not just solid and water but also air emissions and nutrient loss is critical to the framework. A city that reduces resource consumption per capita while increasing environmental and human health impacting emissions must be considered in any urban metabolism sustainability metric.

CHAPTER 3:
Incorporating LCA to Complement Urban Metabolism in Sustainable Community Assessment

The LCA framework offers several methodological contributions for urban metabolism that, if implemented, would provide more comprehensive city assessment and an improved understanding of resource consumption and waste generation impacts. The two frameworks operate under the founding principle of total accounting of energy and resource flows. Urban metabolism has evolved as the approach for understanding the complexities of resource use and waste generation in cities and how technical and socioeconomic development are linked. LCA has been developed as the approach for understanding cradle-to-cradle effects of direct, indirect, and supply chain processes of large systems and the impact those systems have. The two frameworks, however, have developed independently of each other even though many methodological concepts overlap. The incorporation of indirect and supply chain inventorying as well as impact assessment would offer several improvements to the urban metabolism framework and aid in more comprehensively evaluating city sustainability.

3.1 Implementing System Boundaries That Incorporate Indirect and Supply Chain Effects

The establishment of system boundaries in the urban metabolism framework that captures life-cycle processes will improve input and output modeling ultimately resulting in a more comprehensive understanding of city footprints. The challenge of establishing system boundaries that incorporate large system interdependencies has been acknowledged [Fung 2005, Ekvall 2004, Suh 2004, Hendrickson 1998]. Macroregion, nation, and global models may exist but can be constrained by low-resolution and high-uncertainty data, the inability to capture economies of scale, and allocation issues, to name a few. However, by acknowledging and addressing these limitations [Huijbregts 2001], the implementation of large system boundaries that capture supply chains effects can offer critical insight into upstream components that may dominate the footprint of the city but be unaccounted for in the traditional urban metabolism system boundary. (The term *traditional* is used to describe urban metabolism studies typically considering only direct effects of processes.) For example, Chester (2010) performs a LCI of passenger transportation in three U.S. cities concluding that the majority of SO_2 and PM_{10} emissions do not result from vehicle operation combustion emissions but from upstream supply chain processes (SO_2 emissions, which in the lifecycle are a magnitude times larger than the tailpipe, result from electricity generation in vehicle manufacturing, infrastructure construction, and fuel refining, while PM_{10} emissions are produced primarily from aggregate mining for roadways and asphalt placement processes). LCA has introduced a suite of techniques and datasets for evaluating upstream components which should be incorporated in future urban metabolisms. Figure 3 generalizes a traditional urban metabolism system boundary with an expanded boundary that incorporates indirect and supply chain components.

Figure 3: Traditional Urban Metabolism System Boundary With Life-Cycle Indirect and Supply Chain Components and Expanded System Boundary

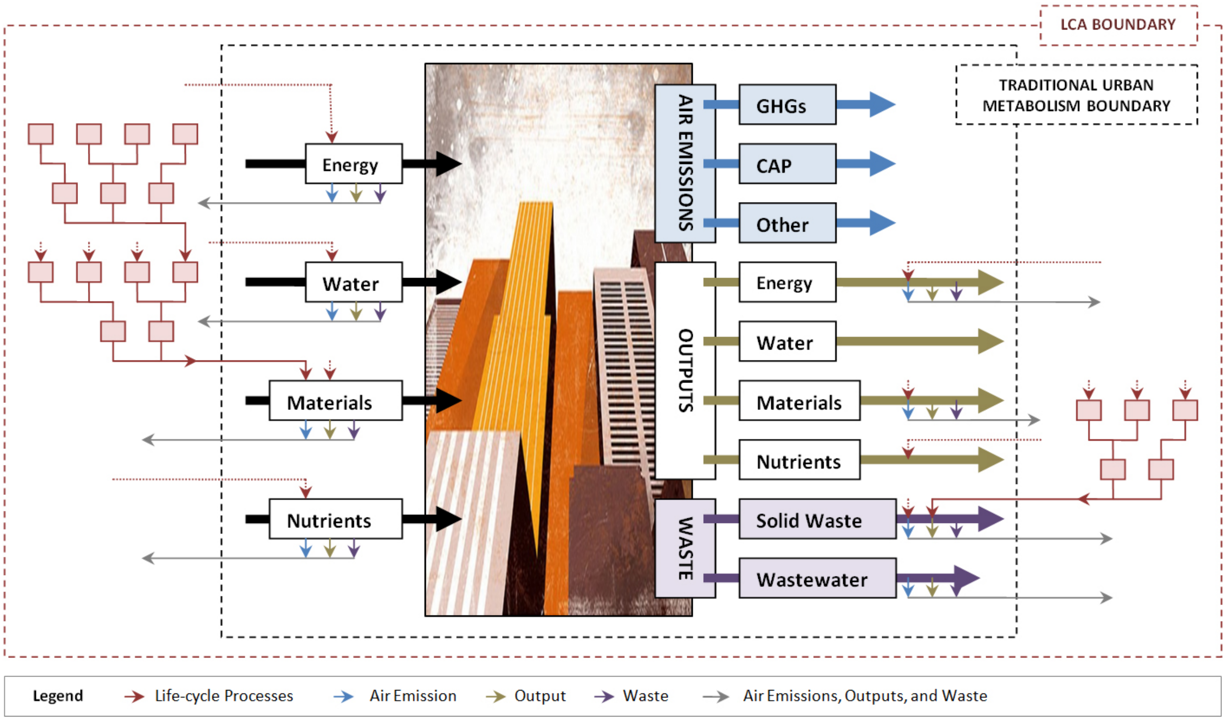


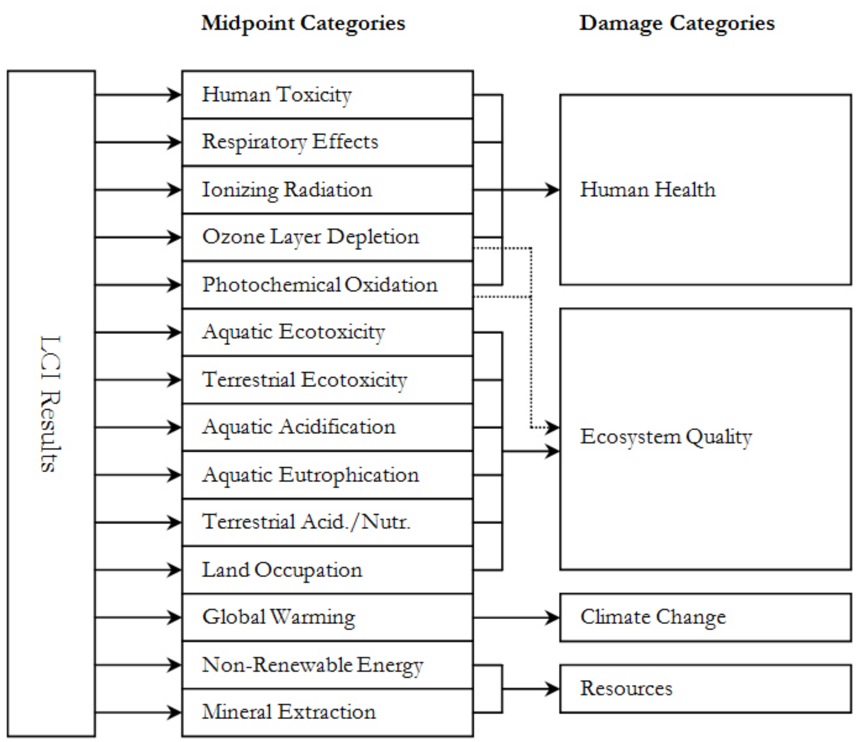
Figure 3 illustrates that for any input or output considered in an urban metabolism framework, indirect and supply chain components can be included to more comprehensively capture the city's footprint. The red arrows represent scenarios where upstream life-cycle components can be included and hypothetical process diagrams are shown for material inputs and solid waste outputs. For example, when considering plastic resin manufacturing to produce polyethylene terephathalate (PET) drink bottles, the urban metabolism framework boundary would consider the mass or embodied energy as one material input to the city. However, evaluating PET materials in the LCA boundary would yield upstream effects not captured in the traditional boundary. EIO-LCA (2010) computes upstream effects for $1 million U.S. dollars' worth of plastic resin manufacturing resulting in 23 Terajoules of energy consumed and emissions of GHG (1,700 Mg CO_2e) and CAP (2.9 Milligrams SO_2, 7.6 Mg Carbon Monoxide, 2.5 Mg NO_X, 5 Mg VOC, and 470 kg PM_{10}). Furthermore, based on data from the U.S. EPA's Toxic Release Inventory, EIO-LCA (2010) reports air (730 kilograms), water (120 kg), and land (460 kg) legal releases of toxic substances directly into the environment. For the 23 TJ of life-cycle energy consumed, 7.9 TJ are the result of direct manufacturing process followed by 4.1 TJ in electricity generation and 2 TJ in petroleum refineries. (The remainder is distributed throughout other supporting processes.) Similarly, of the 1,700 Mg CO_2e life-cycle total GHG emissions, only 400 Mg are emitted during resin manufacturing with significant contributions from electricity generation (340 Mg), chemical manufacturing (90 Mg), and truck transportation (55 Mg). The largest contributors to life-cycle CAP emissions are often not the result of the resin manufacturing itself. Approximately 60 percent of total SO_2 emissions result from electricity generation, 50 percent of total VOC emissions are produced by indirect processes, and the largest PM_{10} contributor is waste management (diesel vehicles handling waste for processes that support resin manufacturing). Figure 3 also calls attention to life-cycle considerations for city outputs by illustrating a hypothetical upstream life-cycle process for solid waste. Waste management processes and the ultimate fate of materials (i.e., landfilling, recycling, reuse, and incineration) can determine the environmental balance of disposed goods [Chester 2008]. Diesel trucks are used for hauling waste and moving materials into landfills. Products that are reused or recycled to some extent avoid manufacturing of new products with more environmentally intense virgin material processing. And the fate of landfill methane gas (i.e., vented with no recovery, captured and flared, or captured and converted to electricity) can shift the GHG balance of entire systems [Chester 2009b]. Kennedy (2007) proposes a general estimate that the area required to sustain a city is typically one or two orders of magnitude greater than the area of the city itself. By extending the urban metabolism traditional boundary with the LCA framework, the reach of the city and the supporting footprint expand by acknowledging all interrelated components. However, this footprint does not yet necessarily incorporate degradation to the environment and human health, a core metric for evaluating urban sustainability.

3.2 Evaluating Impacts

Urban metabolism should be integrated with LCIA in sustainable community evaluation to consider environmental, human health, LCCA, autochthonous resource consumption, labor, and other effects in addition to climate change. The term sustainability is sometimes tied explicitly to GHG emissions and climate change but should consider the suite of impacts that affect not only environmental and human health impacts, but also economic, technical, social, and political conditions. Figure 4 shows the typical impact assessment midpoint categories considered by environmental LCIA practitioners.

The midpoint categories are represented in terms of an equivalence of a reference substance to normalize multiple LCI result substances contributing to the same impact. For example, human toxicity encompasses carcinogenic and non-carcinogenic releases represented as equivalent kilograms of chloroethylene into air [Jolliet 2003]. Then, using exposure models, the human health damage category is estimated. A LCIA may evaluate multiple midpoint categories and would represent the effects to human health in terms of a damage unit, in this case disability adjusted life years (DALY). The environmental and human health midpoint and damage categories shown in Figure 4 do not capture other impacts such as costs, autochthonous resource consumption (e.g., water), or labor. Scoping the definition of sustainability to include considerations for all of these impacts is important from a policy and decision-making perspective. Decisions are rarely made on environmental considerations only and often include economic technical, social, and political components that may constrain options. Also, by considering a single impact (e.g., GHG emissions) a risk exists of substituting a sustainability improvement from one category for increased impacts in another category. This is highlighted by Chester (2010b) in an analysis of California’s proposed high-speed rail (HSR) system. The LCI shows that while it is possible to achieve GHG emissions reductions in implementing the system, if electricity is purchased from the current mix, then increased SO_2 emissions will result in environmental acidification and cardiovascular issues. The takeaway is that any policy that promotes construction of the HSR system should include mandates for cleaner sulfur electricity production (e.g., purchasing high-priced but cleaner electricity or installing advanced scrubber technologies at electricity generation facilities).

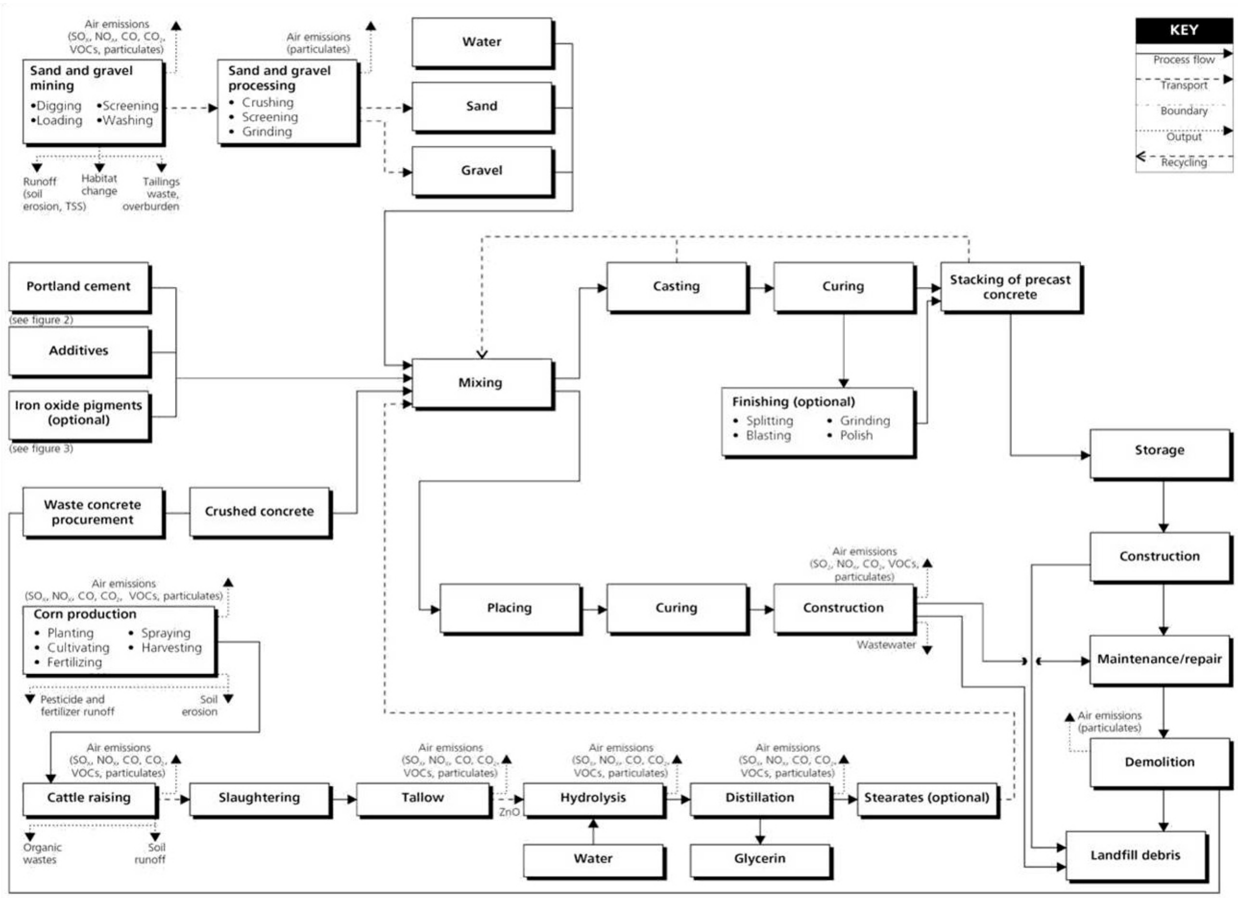
Figure 4: Environmental and Human Health LCIA Categories



[Adapted from Jolliet (2003). Solid lines represent pathways that are known or assumed to exist. Dotted lines represent uncertain impact pathways that are not modeled quantitatively.]

Urban metabolism impact assessment should incorporate LCA and LCIA methodology and move beyond inferring meaning from material flow and accumulation. While understanding accumulation processes is important for sustainable city development allowing inferences about continued consumption growth and the ability of the hinterlands to provide inputs and process waste outputs, it is also important to establish firm cause-and-effect relationships on the environment and people. Integrating LCA with urban metabolism will allow for more comprehensive inventorying, however, the LCIA approach can be used with the traditional system boundary (Figure 3). First, urban metabolism studies should begin linking production, use, and end-of-life environmental, human health, economic, and other indicator factors in evaluating flows into and out of a city. For example, in considering construction materials in the traditional urban metabolism boundary, concrete would enter the city in the form of cement, aggregate, and water leading to energy consumption and emissions in transport. The activities associated with mixing and pouring of concrete will also require diesel fuel and will result in additional emissions [Guggemos 2005]. Lastly, at the end of the concrete's useful life, equipment and manpower will be used to tear it up and remove it from the city, potentially recycling some fraction. An inventory can be created for these components, or expanded with the LCA approach resulting in a more comprehensive assessment. Regardless, in addition to the concrete material flow captured, potential environmental and human health perturbations can be assessed. Expanding the boundary of the study to include LCA considerations would capture components such as mining of raw aggregate and the inputs and outputs associated with those processes. A geographically differentiated resource extraction and depletion LCIA could be developed providing a clearer answer on what continued per capita material consumption means for a particular city. Tracing through the supply chain to specific mining operations would show how quickly mine supply will run out and where the city will need to import from afterwards. (Life-cycle processes associated with concrete are shown in Figure 5.) Furthermore, mining operations release significant quantities of particulate matter [EIO-LCA 2010]. If populations are exposed to emissions from mines when extracting concrete components for a city then human health impacts from a decision in an urban area could be impacting people elsewhere, an important consideration in establishing sustainable practices. The implementation of LCIA in urban metabolism provides a clearer approach for moving beyond inferences of the effects of quantities of inputs and outputs to a methodology that can evaluate these effects.

Figure 5: LCI of Concrete [AIA 1997]



Implementing LCA and LCIA with urban metabolism can aid in evaluating economic, technical, social, and political considerations of decisions. First, LCCA can determine economic impacts beyond direct process costs. For example, externalities associated with air pollution (health care) and resource depletion (having to engineer out materials that are no longer in supply for more costly alternatives or alternatives that are further away) can be included. With the LCA framework, these costs can be geographically and temporally specified to further identify if particular population groups are disproportionally impacted by activities or decisions in the city. Next, because the LCA framework calls for an interpretation phase, the processes producing the greatest impacts should be re-evaluated for potential reductions [ISO 2006]. Technical process scrutiny is important in LCA because it forces evaluation of alternatives and decisions to reduce impact. In evaluating the life-cycle impacts of passenger transportation in cities, Chester (2010) reports emissions of particulate matter from asphalt paving and production are roughly twice that of vehicle operation for automobiles. The interpretation phase suggests further assessment of this result to reduce impact. These emissions are primarily the result of diesel truck use in asphalt paving and fugitive emissions at hot-mix asphalt plants. Solutions could include improved particle filter deployment for diesel trucks and plants, resulting in implementation costs but also avoided human health impacts (that could be evaluated in the LCCA). Or, policies could be implemented such that new asphalt plant facilities are not sited near high impact population areas. Social considerations for LCA can be evaluated to some extent within the LCCA and LCIA frameworks considering to which population groups costs and impacts are disproportionally assessed. Research evaluating the siting of "locally undesirable land uses" could include LCCA and LCIA analyses in the evaluation of burdens for environmental justice concerns [Faber 2002, Hamilton 1995, Been 1993]. Although this does not address all of the broad questions that arise in social equity considerations, it does provide a framework for a quantitative starting point. In evaluating the life-cycle effects of bus operation, Chester (2009a) highlights the importance of considering occupancy levels in the relative environmental benefit of the mode compared to others. Political constraints are important because they may limit choices for reasons that are not captured in material flow or environmental assessments. Bus size in the United States is somewhat constrained by consideration for handicapped accessibility (a benefit that would not be captured in most assessments). Technical recommendations without regard for this political consideration would not produce reasonable options for improvements.

3.3 Closing the Loop

Cradle-to-cradle assessment is a critical step in understanding the complete life cycle because of the potential to avoid production of virgin materials their upstream processes. However, end-of-life processes are often difficult to assess given lack of information on waste systems, resulting in many LCAs establishing system boundaries excluding this step. Nonetheless, with increased waste management constraints (e.g., difficulty in siting new landfills, product take-back regulations, and regional goals for decreased material sent to landfills), it has become more important to consider end-of-life processes. This life-cycle component is not necessarily trivial and can tip the balance of a decision of which product to use. For example, Chester (2008) evaluates changes to a city's recycling operations and resulting increases in recycling participation. The goal of the study was to understand the energy, GHG, and economic effects of modifying collection fleet operations to encourage residents to recycle more (i.e., switching to single-stream recycling requires less effort for residents but more processing of the waste). Chester (2008) shows that with increased recycling comes decreased virgin material use, and the energy and GHG benefits of not extracting and processing virgin material are several orders of magnitude larger than the additional energy and GHG costs of the logistical changes. When surveying a California material recovery facility, Chester (2008) discovered that low-grade recyclables were being shipped to China where they were either processed into new goods or incinerated for electricity. This example highlights the importance of understanding the end-of-life implications for cities and waste outputs.

The uncertainty in waste flows and end-of-life fates should be considered in city LCAs. Some data exist on national waste flows, but little is known at state or regional levels. California compiles more comprehensive data than other states, but the information is focused on characterizing the composition of solid waste and landfills, neither specifically addressing flows [CIWMB 2008]. The environmental impacts from waste in landfills is also uncertain. While landfills are discussed as GHG sources (due to anaerobic decay-producing methane), the body of literature addressing landfill chemistry is sparse and points to significant uncertainty in GHG emission factors [Chester 2009b]. Waste buried at landfills may or may not degrade depending on the material's lignin content and other environmental factors; and it is possible for landfills to sequester carbon [Chester 2009b, EPA 2006]. Methane that is produced is either not captured and vented to the atmosphere, captured and flared (reducing the methane to CO_2 resulting in fewer GHG impacts and destroying organic compounds which pose human health risks), or captured and combusted for electricity. The capture efficiency is also somewhat uncertain with a large range. (Chester 2009b summarizes literature reporting between 10 percent and 90 percent of gas collected.) However, significant development of gas-to-energy systems coupled with financial incentives to overcome initial investments may further aid in the deployment of these technologies [EPA 2010b]. Gas-to-electricity can reduce GHG impacts by reducing landfill direct emissions and offsetting fossil-based electricity production. Although significant uncertainty exists for end-of-life processes, incorporating this component into urban metabolism is necessary to understand how material and energy loops are closed. This includes both the effects of material end-of-life choices as well as how those choices affect the larger system (for example, avoiding virgin use). Previous LCAs that incorporate this component suggest that including it can alter decisions on how to design and use products, and dispose of waste.

3.4 First Steps

Integrating the LCA framework with urban metabolism can be assisted by several studies that have already evaluated components of urban environments. LCAs have been executed for energy, materials, water, nutrients, and waste footprints of cities or their components. Identifying the need to include LCA in material flow analysis, Leach (1997) evaluates the paper life cycle presenting initial thoughts on the need for integrating the two approaches for cities. Water and wastewater LCIs and LCIAs for several cities have been performed including evaluation of conventional technologies and future improvements [Lundie 2004, Lundin 2002, Lundin 2000, Houillon 2005, Tillman 1998]. Several of the wastewater studies link changes in processing steps to effects on upstream mineral production. The material and environmental impacts of buildings has been considered. Guggemos (2005) and Eaton (1998) create LCAs for comparing concrete and steel-framed buildings. Guggemos (2006) presents an LCI decision-support tool for evaluating commercial building construction, and Junnila (2006) and Junnila (2003) quantify the LCI of office buildings in Europe and the United States. Through evaluation of construction materials, building operations, and transportation effects, Norman (2006) evaluates the energy and GHG life-cycle effects of high and low residential density. The life-cycle effects of waste management including landfill gas capture is of particular interest to LCA practitioners trying to better understand end-of-life scenarios. Chester (2008) evaluates how changes in collection logistics for a city improves recycling participation rates, ultimately avoiding virgin material production. Denison (1996) and Barton (1996) present discussions on the importance of life-cycle considerations in waste management. LCAs of city components also exist for processes that do not fit into the traditional urban metabolism inputs and outputs. Chester (2010) compares passenger transportation impacts in the San Francisco, Chicago, and

New York areas, Blazek (1999) contrasts telecommunications systems in Stockholm, Sweden, and Sacramento, California, and Arditi (1999) examines how municipalities perform LCCA.

Regional datasets and input-output models should be developed to facilitate the integration of LCA and urban metabolism. There are few state and city-level material flow data [Cicas 2007] and energy, emissions, and other waste factors are often not geographically specified. Chester (2009b) points out that little state-level data exists on the landfill gas capture technologies for California landfills. To evaluate the changes in California landfill emissions from reductions of solid waste, Chester (2009b) developed California-specific landfill emission factors from national average factors [EPA 2006]. The use of state-level electricity mix environmental factors also is problematic because it does not acknowledge interstate power trading. Marriott (2005) discusses how environmentally progressive policies have pushed coal generation out of California and imports of electricity accounted for 26 percent of total electricity consumption for the state in 2000. It is necessary to evaluate city-specific factors because of the potentially large estimation errors that could result from implementation of lower resolution parameters. While some state-level input-output models exist [EIO-LCA 2010], many new region-specific datasets will need to be developed before supply chain effects can be accurately determined for urban areas. Additionally, impact assessment will also need to be assessed with high geographic resolution. There are number of impact assessment tools that can evaluate the environmental and human health effects at high resolution (e.g., county-level) [Humbert 2009, Muller 2007]. The use of state or national factors for urban analysis can insert a level of uncertainty into results that may lead to incorrect policy decisions.

CHAPTER 4:
Urban Policy and Systems-oriented Approaches

Policy has rarely incorporated system-wide assessment and it has become increasingly important to do so with an improved understanding of the interconnectedness of processes. Moving beyond assessments of direct processes of interest to capture indirect and supply chain effects is necessary in forming comprehensive regulations. It is important that reductions in one environmental impact are not traded for another.

4.1 Acknowledging Indirect and Supply Chain Processes

Combining LCA with urban metabolism creates a new conceptual framework for constructing policy that considers beyond direct processes. With increasing interest in reducing climate change impacts, geographic regions from sub-national authorities to the city level have constructed greenhouse gas reduction plans [WCI 2010, CARB 2010a, CARB 2010b, Portland 2009]. These plans seek reductions through direct (e.g., energy efficiency, vehicle standards, renewable electricity goals, reducing automobile trips, etc.) and economic mechanisms. A commonality of these plans is that they typically focus on reductions of greenhouse gases without consideration of life-cycle effects (one exception being California's Low Carbon Fuel Standard which introduces fuel life-cycle carbon-intensity evaluation). To exclude indirect and supply chain effects is short-sighted because 1) life-cycle effects will change inventory results and 2) it may be possible for a city to reduce its footprint by improving life-cycle processes by targeting upstream processes outside of their region (e.g., requiring suppliers of goods to consolidate shipments so that freight operations that provide upstream logistics for goods that ultimately end up in the city are less carbon-intense).

California's Senate Bill 375 (SB375) links regional planning and transportation with the goal of controlling urban sprawl (ultimately reducing vehicle travel and its emissions) and should include systems-oriented GHG accounting. The bill requires that the 18 metropolitan planning organizations within the state align transportation, housing, and regional land-use plans with the goal of reducing vehicle travel [CARB 2010b]. The objective is that by requiring regional GHG plans that indirectly control vehicle travel, communities will have to integrate disjointed processes and organizations that are involved in developmental processes to create integrated sustainable growth strategies. While SB375 is still in its initial phases and is likely subject to re-evaluation in its regulatory process, it has not introduced systems-oriented GHG accounting to comprehensively evaluate its effects. The GHG accounting metrics are not clear but it is implied that regions evaluate reductions in automobile travel in their plans through fuel combustion emissions. The tailpipe approach can yield informative indicators but the LCA and urban metabolism frameworks should be applied to accurately quantify system-wide effects.

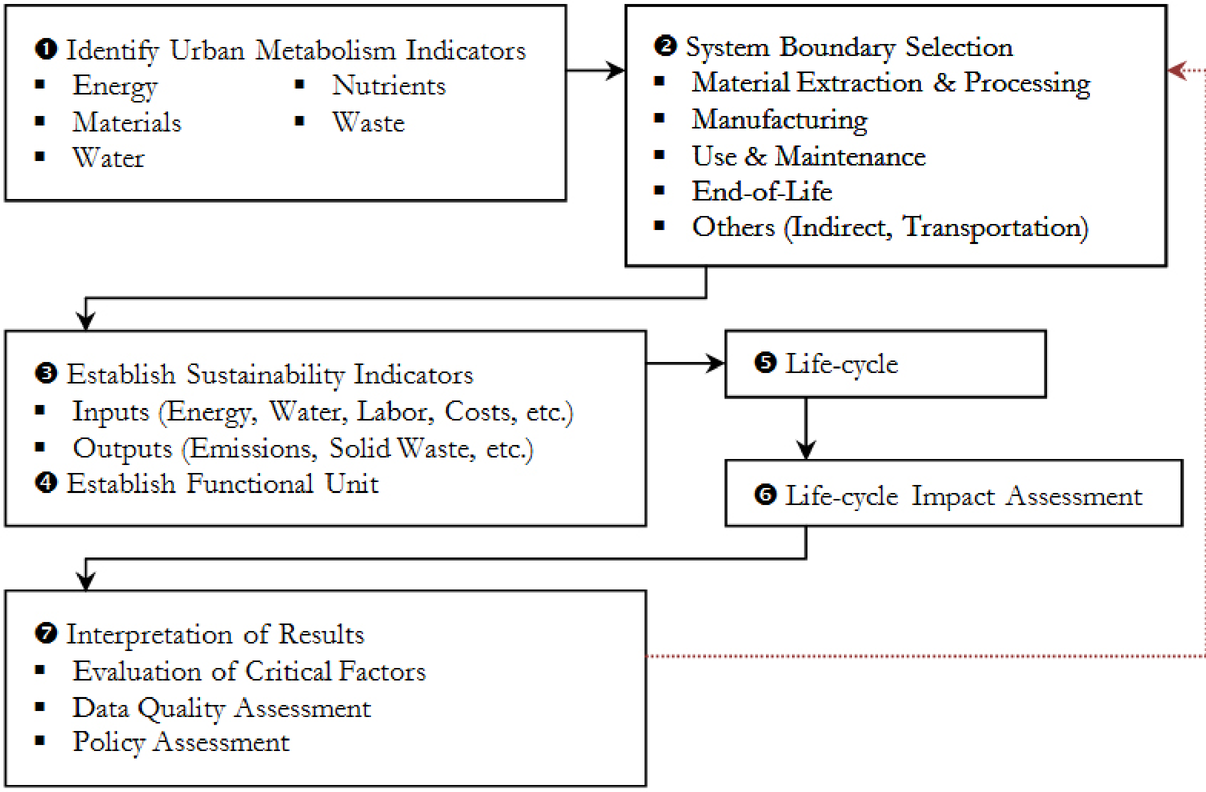
SB375 should acknowledge that changes in personal vehicle travel through sustainable growth result in emissions effects beyond the tailpipe. For example, instead of building tract homes on the city periphery at low development costs and high returns, SB375 now incentivizes the developer to construct closer to the city center where public transit and non-motorized modal access is more effective. Evaluating the two scenarios may in fact show that additional automobile travel was avoided with their GHG emissions. However, the LCA framework specifies more comprehensive evaluation of the two scenarios including infrastructure components. The additional energy requirements and emissions of constructing in the two regions should be included as well as the effects of residential building density on facility operations [Norman 2006]. Indicators are that high residential density, which syncs with sustainable growth SB375 objectives, reduces both vehicle travel and infrastructure requirements producing additional savings not accounted for when evaluating the automobile's fuel combustion explicitly. While building GHG emissions are larger for high density-development per square meter than low-density, residents in high-density areas often live in smaller dwellings resulting in lower emissions per person [Norman 2006]. And many components beyond building construction and operation should be considered. Building on the city periphery will result in a loss of productive natural environment, a potentially significant life-cycle GHG component (as illustrated for biofuels by Searchinger 2008). Furthermore, reducing combustion emissions through reductions in vehicle travel also reduces emissions associated with fuel production and vehicle manufacturing and maintenance (reductions in distance driven extends the temporal lifetime of automobiles, delaying the need to construct a new vehicle and perform maintenance) [Chester 2009a].

The goal of SB375 is to reduce GHG emissions indirectly and the urban metabolism framework offers an approach for evaluating the multiple energy and environmental indicators of processes that are ultimately targeted for carbon reductions. GHG emissions would be considered an airborne waste in the tradition urban metabolism boundary. Current SB375 accounting suggests evaluation of the airborne waste without any consideration of the system-wide changes of inputs and outputs that occur. This approach is prone to missing the indirect effects that occur elsewhere in the city in energy, water, material, nutrient, and other waste flows. Cross-assessments of these components are commensurate with the LCA framework in their fundamental methodological consideration that systems are not independent and should not be evaluated as such. Reducing vehicle travel through sustainable develop would affect consumption of energy, water, material, and nutrients, and would change other waste flows. For example, high-density residential development can result in less energy use (due to shared wall effects), a less expansive water infrastructure, differing building material requirements, changes to nutrient recycling, and new waste flows compared to low-density sprawl. Each of these changes presents a potential change in GHG emissions unrelated to vehicle travel. The SB375 goal of implementing smart growth strategies for communities should be evaluated from systems-oriented lenses that capture the broader scale of GHG impacts.

4.2 Performing LCA With Urban Metabolism

Urban sustainability analysis can be accomplished by adapting traditional LCA guidelines in the assessment of city metabolism indicators [ISO 2006]. Figure 6 shows a generalized analysis process for evaluating urban metabolism indicators.

Figure 6: Combined LCA and Urban Metabolism Analysis Process



The analysis starts with the identification of urban metabolism indicators of interest (Figure 6: ❶). Urban metabolism studies typically consider only a few of these indicators in their assessments [Kennedy 2007], and comprehensive city analysis should capture all inputs and outputs if possible. With urban metabolism indicators selected, the system boundary is established to capture the direct, indirect, and supply chain components that should be captured in the LCI (Figure 6: ❷). Not all life-cycle components need to be included in every LCA. LCAs that evaluate policies or decisions that affect particular life-cycle stages where other stages do not change may exclude these components. Decisions that affect the energy efficiency of manufacturing processes may not result in changes to upstream components. The selection of the system boundary is possibly the most critical component in the LCA process because if critical processes are excluded, then policy and decision recommendations may be poorly informed. Considering the many human health and environmental indicators that can be included in the definition of sustainability is important (Figure 6: ❸). Establishing sustainability metrics based on a subset of indicators may result in unforeseen impact tradeoffs. Sustainability should include not only human health and environmental metrics, but also factors that capture economic, social, technical, and political requirements. All indicators must be normalized to a functional unit (or multiple) that captures accurate representation of effects (Figure 6: ❹). For example, consider a comparison of two cars. One may emit 250 g CO_2e per vehicle kilometer and the other 350 g CO_2e per vehicle kilometer. If the first car typically travels with just the driver and the second a driver and carpooling passenger then depending on the study goal it may be more informative to measure the emissions per passenger kilometer (the first car would emit 250 g CO_2e per passenger kilometer and the second 175 g CO_2e) since the ultimate goal of passenger transportation modes is to move people and not vehicles. In this example, evaluating per vehicle and passenger kilometer would lead to two different sets of policy options.

Having established the scope and metrics for evaluating the city, the LCI would be executed (Figure 6: ❺). The inventory would evaluate each process within the system boundary for the input and output environmental indicators of interest normalizing them to the functional unit. The inventory would capture direct, indirect, and supply chain requirements for each process. The approaches and data available to develop LCIs are numerous. Literature and software tools should be employed when analyzing particular subsystems to understand the processes involved and the indirect and supply chain requirements. Once completed, the LCI should be expanded to an impact assessment so that total inputs and outputs do not stand as representation of the actual human health, environmental, and other burdens that are ultimately of concern (Figure 6: ❻). The final phase in the analysis is interpretation of results where critical system factors, data quality, and policy are evaluated (Figure 6: ❼). Furthermore, this phase becomes not the ending point of the assessment but the first step for improvement through re-evaluation. Having identified the critical factors, data quality improvements needed, and policies, the evaluation should commence again with process changes so that indicators are developed for improving both the analysis and burdens.

4.3 Data Quality Assessment and Gaps

While many LCAs exist for city processes or components, low-quality data and gaps still exist and should be addressed to aid in the joining of the two frameworks. Process data for particular stages of the LCA may not exist or may exist at too coarse geographic resolution and should be developed or gathered. The urban metabolism framework's evaluation of energy, water, materials, nutrients, and wastes when combined with LCA should evaluate cradle-to-cradle processes. (See Figure 1.) Urban sustainability practitioners should start by identifying these data quality issues for each of the five city indicators. Methods exist for evaluating data quality in LCA and the underlying data gaps. The Data Quality Assessment Pedigree Matrix in Table 1 presents indicator criteria for evaluating the quality aspects of data use in large systems. When evaluating a particular data point, process, or component, the practitioner would step through each criteria and assign an indicator score. This would be done for all (if feasible) or critical data points in the assessment and used to rank the overall quality of each factor. The final scores would then be used in the interpretation phase to re-evaluate critical data to improve quality.

Table 1: Data Quality Assessment Pedigree Matrix

Criteria	Indicator Score				
	1	**2**	**3**	**4**	**5**
Impact on Final Result	Parameter is the top contributor to final result	Parameter is within the top 5 contributors to final result	Parameter is within the top 10 contributors to final result	Parameter is not likely to affect final results significantly	Parameter contribution is unknown
Acquisition Method	Measured data	Calculated data based on measurements	Calculated data partly based on assumptions	Qualified estimate (by industrial expert)	Nonqualified estimate
Independence of Data Supplier	Verified data, information from public or other independent source	Verified information from enterprise with interest in the study	Independent source, but based on nonverified information from industry	Nonverified information from industry	Nonverified information from the enterprise interested in the study
Representation	Representative data from sufficient sample of sites over and adequate period to even out normal fluctuations	Representative data from smaller number of sites but for adequate periods	Representative data from adequate number of sites, but from shorter periods	Data from adequate number of sites, but shorter periods	Representativeness unknown or incomplete data from smaller number of sites and/or from shorter periods
Temporal Correlation	Less than three years of difference to year of study	Less than five years of difference	Less than 10 years of difference	Less than 20 years of difference	Age unknown or more than 20 years of difference
Geographical Correlation	Data from area under study	Average data from larger area in which the area of study is included	Data from area with similar production conditions	Data from area with slightly similar production conditions	Data from unknown area or area with very different production conditions
Technological Correlation	Data from enterprises, processes and materials under study	Data from processes and materials under study, but from different enterprises	Data from processes and materials under study, but from different technology	Data on related processes or materials, but same technology	Data on related processes or materials, but different technology
Range of Variation	Estimate is a fixed and deterministic number	Estimate is likely to vary within a 5% range	Estimate is likely to vary within a 10% range	Estimate is likely to vary more than 10%	Estimate is likely to vary under unknown ranges

(Adapted from Huijbregts 1998, Lindfors 1995, and Weidema 1996)

The data quality assessment process can be used to evaluate processes or LCA components in addition to single data points. For example, when evaluating material use by cities, the practitioner should consider extraction of raw material inputs, processing into new products, manufacturing into the material of interest, use, disposal (i.e., recycling, landfilling, etc.), and transportation between all phases. In evaluating any of these life-cycle components for the material of interest, environmental indicators of interest would be inventoried (e.g., energy inputs, emission outputs). Table 1's pedigree matrix would be used to create Table 2's data quality assessment matrix.

Table 2: Hypothetical Data Quality Assessment Matrix for City Material Use

Component	Impact on Final Result	Acquisition Method	Independence of Data Supplier	Representation	Temporal Correlation	…
Raw Material Input Extraction						
Raw Input Processing						
Manufacturing						
Use						
End-of-Life						
…						

(Adapted from the structure presented in Table 1)

For each cell of the matrix, Table 1's definitions would be used to score the component. The scores would then be totaled or averaged and the higher the result, the lower the quality and the greater the need for improvement. This method provides a means for evaluating the complexities of large data requirements in LCA and urban metabolism ultimately providing a metric to improve quality and fill in data gaps. Abbreviations

4.4 Regrettable Substitutions

Policy and decision-making should consider the suite of environmental and human health impacts in conjunction with technical, social, and economic constraints when crafting regulation. As highlighted in Figure 4, environmental and human health impacts take on many forms. And as illustrated with California HSR, mandates to reduce carbon emissions should be implemented with consideration for other impacts. Comprehensive environmental policy that incorporates LCA and urban metabolism will have the foresight needed to craft regulations that simultaneously reduce multiple impacts. It will also provide a means for evaluating environmental, technical, social, and economic considerations together. California's Assembly Bill 32 (ARB 32) sets GHG reduction targets for the state through 18 emissions reductions measure [CARB 2010a]. One of these measures is HSR and if constructed will result in one Tg CO_2e avoided, a small fraction of the 427 Tg CO_2e reductions needed to meet 2020 targets [CARB 2010a]. However, the economic investment in such a system is large and a potential barrier to constructing the system. Furthermore, the cost per unit of GHG avoided is almost certainly different than the alternatives. Given a limited budget to implement reductions, ARB 32 decision-makers would have to choose the most effective spending option eliminating certain measures. Technical limits may appear in the same manner requiring evaluation of practical implementation of mechanisms.

Incorporating the LCA and urban metabolism frameworks into sustainable community assessment provides a more comprehensive environmental outlook and avoids regrettable substitutions. The recommendation to incorporate these approaches does not need to manifest as an analytical exercise but can be applied as qualitative assessments. Any policy that seeks to improve the environmental well-being of a community should avoid regrettable substitutions, the tradeoff of one environmental impact for another. And quantitative or qualitative assessments with the proposed frameworks should help illustrate the connections between impacts. With increased attention on environmental and human health impacts, sustainable community policy should adopt systems-oriented thinking to form a more rigorous understanding of the direct, indirect, and supply chain processes associated with each resource input and waste output.

REFERENCES

American Institute of Architects (AIA), 1997, *Environmental Resource Guide Supplement*, Wiley and Sons.

Arditi D. and Messiha H.M., 1999, *Life Cycle Cost Analysis (LCCA) in Municipal Organizations*, ASCE Journal of Infrastructure Systems 5(1) 1-10 [available online at http://dx.doi.org/10.1061/(ASCE)1076-0342(1999)5:1(1)].

Barles S., 2009, *Urban Metabolism of Paris and its Region*, Journal of Industrial Ecology 13(6) 898-913 [available online at http://dx.doi.org/10.1111/j.1530-9290.2009.00169.x].

Barles S., 2007, *Feeding the City: Food Consumption and Flow of Nitrogen, Paris, 1801–1914*, Science of the Total Environment 375(1-3) 48-58 [available online at http://dx.doi.org/10.1016/j.scitotenv.2006.12.003].

Barton J.R., Dalley D., and Patel V.S., 1996, *Life Cycle Assessment for Waste Management*, Waste Mangement 16(1-3) 35-50 [available online at http://dx.doi.org/10.1016/S0956-053X(96)00057-8].

Been V., 1993, *What's Fairness Got To Do With It? Environmental Justice and the Siting of Locally Undesirable Land Uses*, Cornell Law Review 78(6) 1001-1085 [available online at http://heinonline.org/HOL/Page?collection=journals&handle=hein.journals/clqv78&id=1069]

Blazek M., et al., 1999, *Tale of Two Cities: Environmental Life Cycle Assessment for Telecommunications Systems: Stockholm, Sweden and Sacramento, CA*, Electronics and the Environment, Proceedings of the 1999 IEEE International Symposium on Electronics and the Environment, 76-81 [available online at http://dx.doi.org/10.1109/ISEE.1999.765852].

Bouman M., et al., 2000, *Material Flows and Economic Models: An Analytical Comparison of SFA, LCA and Partial Equilibrium Models*, Ecological Economics 32(2) 195-216 [available online at http://dx.doi.org/10.1016/S0921-8009(99)00091-9].

California Air Resources Board (CARB), 2010, *Assembly Bill 32: Global Warming Solutions Act of 2006*, Sacramento, CA [background information available online at http://www.arb.ca.gov/cc/ab32/ab32.htm, accessed March 19, 2010].

California Air Resources Board (CARB), 2010, *Senate Bill 375* [background information available online at http://www.arb.ca.gov/cc/sb375/sb375.htm, accessed March 19, 2010].

Chester M.V., Martin E., and Sathaye N., 2008, *Energy, Greenhouse Gas, and Cost Reductions for Municipal Recycling Systems*, Environmental Science and Technology 42(6) 2142-2149 [available online at http://dx.doi.org/10.1021/es0713330].

Chester M.V. and Horvath A., 2009, *Environmental Assessment of Passenger Transportation Should Include Infrastructure and Supply Chains*, Environmental Research Letters 4(2) [available online at http://dx.doi.org/10.1088/1748-9326/4/2/024008].

Chester M.V. and Martin E., 2009, *Cellulosic Ethanol from Municipal Solid Waste: A Case Study of the Economic, Energy, and Greenhouse Gas Impacts in California*, Environmental Science and Technology 43(14) 5183-5189 [available online at http://dx.doi.org/10.1021/es802788z].

Chester M.V., Horvath A., and Madanat S., 2010, *Comparison of Life-cycle Energy and Emissions Footprints of Passenger Transportation in Metropolitan Regions*, Atmospheric Environment 44(8) 1071-1079 [available online at http://dx.doi.org/10.1016/j.atmosenv.2009.12.012].

Chester M.V. and Horvath A., 2010, *Life-cycle Assessment of High-Speed Rail: The Case of California*, Environmental Research Letters 5(1) [available online at http://dx.doi.org/10.1088/1748-9326/5/1/014003].

Cicas G. et al., 2007, *A Regional Version of a US Economic Input-Output Life-cycle Assessment Model*, International Journal of Life Cycle Assessment 12(6) 365-372 [available online at http://dx.doi.org/10.1065/lca2007.04.318].

California Integrated Waste Management Board (CIWMB), 2008, *California 2008 Statewide Waste Characterization Study*, California Environmental Protection Agency [available online at http://www.calrecycle.ca.gov/Publications/default.asp?pubid=1346].

Decker E.H., et al., 2000, *Energy and Material Flow Through the Urban Ecosystem*, Annual Review of Energy and the Environment 25 685-740 [available online at http://dx.doi.org/10.1146/annurev.energy.25.1.685].

Denison R.A., 1996, *Environmental Life-cycle Comparisons of Recycling, Landfilling, and Incineration: A Review of Recent Studies*, Annual Review of Energy and the Environment 21 191-237 [available online at http://dx.doi.org/10.1146/annurev.energy.21.1.191].

Duvigneaud P. and Denayeyer-De Smet S., 1977, *L'Ecosystéme Urbs, in L'Ecosystéme Urbain Bruxellois, Productivité en Belgique*, Duvigneaud, P. & Kestemont, P. eds., Traveaux de la Section Belge du Programme Biologique International, Bruxelles, 581-597.

Eaton K.J. and Amato A., 1998, *A Comparative Life Cycle Assessment of Steel and Concrete Framed Office Buildings*, Journal of Constructional Steel Research 46(1-3) 286-287 [available online at http://dx.doi.org/10.1016/S0143-974X(98)00074-1].

Economic Input-Output Life Cycle Assessment (EIO-LCA) tool, Carnegie Mellon University Green Design Institute, US 1997 Industry Benchmark Model [available online at http://www.eiolca.net/, accessed February 23, 2010].

Ekvall T., and Weidema B.P., 2004, *System Boundaries and Input Data in Consequential Life Cycle Inventory Analysis*, International Journal of Life Cycle Assessment, 9(3) 161-171 [available online at http://dx.doi.org/10.1007/BF02994190].

U.S. Environmental Protection Agency (EPA), 2010, *Toxics Release Inventory Program*, http://www.epa.gov/tri/.

U.S. Environmental Protection Agency (EPA), 2010, *Landfill Methane Outreach Program*, http://www.epa.gov/lmop/.

U.S. Environmental Protection Agency (EPA), 2006, *Solid Waste Management and Greenhouse Gases: A Life-cycle Assessment of Emissions and Sinks*, Washington, DC [available online at http://www.epa.gov/climatechange/wycd/waste/reports.html].

U.S. Environmental Protection Agency (EPA), 1993, *Life Cycle Assessment: Inventory Guidelines and Principles*, Report # EPA/600/R-92/245. Washington, DC.

Faber D.R. and Krieg E.J., 2002, *Unequal Exposure to Ecological Hazards: Environmental Injustices in the Commonwealth of Massachusetts*, Environmental Health Perspectives 110(2) 277-288 [available online at http://www.jstor.org/stable/3455064].

Facanha C. and Horvath A., 2007, *Evaluation of Life-Cycle Air Emission Factors of Freight Transportation*, Environmental Science and Technology 41(20) 7138-7144 [available online http://dx.doi.org/10.1021/es070989q].

Facanha C. and Horvath A., 2006, *Environmental Assessment of Freight Transportation in the U.S.*, International Journal of Life Cycle Assessment 11(4) 229-239 [available online at http://dx.doi.org/10.1065/lca2006.02.244].

Færge J., Magid J., and Penning de Vries F.W.T., 2001, Urban Nutrient Balance for Bangkok, Ecological Modeling 139(1) 63-74 (available online at http://dx.doi.org/10.1016/S0304-3800(01)00233-2).

Farrell A., et al., 2006, *Ethanol Can Contribute to Energy and Environmental Goals*, Science 311(5760) 506-508 [available online at http://dx.doi.org/10.1126/science.1121416].

Forkes J., 2007, *Nitrogen Balance for the Urban Food Metabolism of Toronto, Canada*, Resources, Conservation, and Recycling 52(1) 74-94 [available online at http://dx.doi.org/10.1016/j.resconrec.2007.02.003].

Fung M. and Kennedy C.A., 2005, *An Integrated Macroeconomic Model for Assessing Urban Sustainability*, Environment and Planning B: Planning and Design 32 639-656 [available online at http://dx.doi.org/10.1068/b31113].

Goodland R. and Daly H., 1996, *Environmental Sustainability: Universal and Non-negotiable*, Ecological Applications 6(4) 1002-1017 [available online at http://www.jstor.org/stable/2269583].

Guggems A, and Horvath A, 2006, *Decision-Support Tool for Assessing the Environmental Effects of Constructing Commercial Buildings*, ASCE Journal of Architectural Engineering 12(4) 187-195 [available online at http://dx.doi.org/10.1061/(ASCE)1076-0431(2006)12:4(187)].

Guggemos A., and Horvath A., 2005, *Comparison of Environmental Effects of Steel- and Concrete-Framed Buildings*, ASCE Journal of Infrastructure Systems 11(2) 93-101]available online at http://dx.doi.org/10.1061/(ASCE)1076-0342(2005)11:2(93)].

Hamilton J.T., 2005, *Testing for Environmental Racism: Prejudice, Profits, Political Power?* Journal of Policy Analysis and Management 14(1) 107-132 [available online at http://www.jstor.org/stable/3325435].

Hendrickson C., Lave L., and Matthews H.S., 2006, *Environmental Life Cycle Assessment of Goods and Services* (Resources for the Future Press, Washington, DC).

Hendrickson C., et al., 1998, *Economic Input-Output Models for Environmental Life-Cycle Assessment*, Environmental Science and Technology 32(7) 184A-191A.

Houillon G. and Jolliet O., 2005, *Life Cycle Assessment of Processes for the Treatment of Wastewater Urban Sludge: Energy and Global Warming Analysis*, Journal of Cleaner Production 13(3) 287-299 [available online at http://dx.doi.org/10.1016/j.jclepro.2004.02.022].

Huang S. and Hsu W., 2003, *Materials Flow Analysis and Emergy Evaluation of Taipei's Urban Construction*, Landscape and Urban Planning 63(2) 61-74 [available online at http://dx.doi.org/10.1016/S0169-2046(02)00152-4].

Huang S., 1998, *Urban Ecosystems, Energetic Hierarchies, and Ecological Economics of Taipei Metropolis*, Journal of Environmental Management 52(1) 39-51 [available online at http://dx.doi.org/10.1006/jema.1997.0157].

Huijbregts M.A.J, et al., 2001, *Framework for Modeling Data Uncertainty in Life Cycle Inventories*, International Journal of Life Cycle Assessment 6(3) 127-132 [available online at http://dx.doi.org/10.1007/BF02978728].

Huijbregts M.A.J., 1998, *Application of Uncertainty and Variability in LCA*, International Journal of Life Cycle Assessment 3(5) 273-280 [available online at http://dx.doi.org/10.1007/BF02979835].

Humbert S., et al., 2009, *Assessing Regional Intake Fractions in North America*, Science of the Total Environment 407(17) 4812-4820 [available online at http://dx.doi.org/10.1016/j.scitotenv.2009.05.024].

International Organization of Standardization (ISO), 2006, *Environmental Management, Life Cycle Assessment, Principles and Framework, 14040* (Geneva, Switzerland).

Jolliet O., et al., 2003, *IMPACT 2002+: A New Life Cycle Impact Assessment Methodology*, International Journal of Life Cycle Assessment 8(6) 324-330 [available online at http://dx.doi.org/10.1007/BF02978505].

Junnila S., Horvath A., and Guggemos A.A., 2006, L*ife-Cycle Assessment of Office Buildings in Europe and the United States*, ASCE Journal of Infrastructure Systems 12(1) 10-17, [available online at http://dx.doi.org/10.1061/(ASCE)1076-0342(2006)12:1(10)].

Junnila S. and Horvath A., 2003, *Life-cycle Environmental Effects of an Office Building*, ASCE Journal of Infrastructure Systems 9(4) 157-166 [available online at http://dx.doi.org/10.1061/(ASCE)1076-0342(2003)9:4(157)].

Kennedy C., et al., 2009, *Greenhouse Gas Emissions from Global Cities*, Environmental Science and Technology 43(19) 7297-7302 [available online at http://dx.doi.org/10.1021/es900213p].

Kennedy C., et al., 2009, *Methodology for Inventorying Greenhouse Gas Emissions from Global Cities*, Accepted for publication in Energy Policy [available online at http://dx.doi.org/10.1016/j.enpol.2009.08.050].

Kennedy C., Cuddihy J., and Engel-Yan J., 2007, *The Changing Metabolism of Cities*, Journal of Industrial Ecology 11(2) 43-59 [available online at http://dx.doi.org/10.1162/jie.2007.1107].

Pfister S., Koehler A., and Hellweg S., 2009, *Assessing the Environmental Impacts of Freshwater Consumption in LCA*, Environmental Science and Technology 43(11) 4098-4104 [available online at http://dx.doi.org/10.1021/es802423e].

Leach M.A., Bauen A., Lucas N.J.D., 1997, *A Systems Approach to Materials Flow in Sustainable Cities: A Case Study of Paper*, Journal of Environmental Planning and Management 40(6) 705-724 [available online at http://dx.doi.org/10.1080/09640569711868].

Leontief W., 1970, *Environmental Repercussions and the Economic Structure: an Input–Output Approach*, The Review of Economics and Statistics, 52(3) 262–271 [available online at http://www.jstor.org/stable/1926294].

Lindfors L., 1995, *Nordic Guidelines on Life-Cycle Assessment*; Nordic Council of Ministers, ISBN 9789291206926.

Lundie S., Peters G.M., and Beavis P.C., 2004, *Life Cycle Assessment for Sustainable Metropolitan Water Systems Planning*, Environmental Science and Technology 38(13) 3465-3473 [available online at http://dx.doi.org/10.1021/es034206m].

Lundin M. and Morrison G.M., 2002, *A Life Cycle Assessment Based Procedure for Development of Environmental Sustainability Indicators for Urban Water Systems*, Urban Water 4(2) 145-152 [available online at http://dx.doi.org/10.1016/S1462-0758(02)00015-8].

Lundin M., Bengtsson M., and Molander S., 2000, *Life Cycle Assessment of Wastewater Systems: Influence of System Boundaries and Scale on Calculated Environmental Loads*, Environmental Science and Technology 34(1) 180-186 [available online at http://dx.doi.org/10.1021/es990003f].

Marriott J. and Matthews H.S., 2005, *Environmental Effects of Interstate Power Trading on Electricity Consumption Mixes*, Environmental Science and Technology 39(22) 8584-8590 [available online at http://dx.doi.org/10.1021/es0506859].

Muller N.Z. and Mendelsohn R., 2007, *Measuring the Damages of Air Pollution in the United States*, Journal of Environmental Economics and Management 54(1) 1-14 [available online at http://dx.doi.org/10.1016/j.jeem.2006.12.002].

Ngo N.S. and Pataki D.E., 2008, *The Energy and Mass Balance of Los Angeles County*, Urban Ecosystems 11(2) 121-139 (available online at http://dx.doi.org/10.1007/s11252-008-0051-1).

Niza S., Leonardo R., and Paulo F., 2009, *Urban Metabolism: Methodological Advances in Urban Material Flow Accounting Based on the Lisbon Case*, Journal of Industrial Ecology 13(3) 384-405 [available online at http://dx.doi.org/10.1111/j.1530-9290.2009.00130.x].

Norman J., MacLean H.L., and Kennedy C.A., 2006, *Comparing High and Low Residential Density: Life-Cycle Analysis of Energy Use and Greenhouse Gas Emissions*, ASCE Journal of Urban Planning and Development, 132(1) 10-21 [available online at http://dx.doi.org/10.1061/(ASCE)0733-9488(2006)132:1(10)].

Odum H.T., 1983, *Systems Ecology, An Introduction* (Wiley-Interscience, New York, NY).

O'Hare, M. et al., 2009, *Proper Accounting for Time Increases Crop-Based Biofuels' Greenhouse Gas Deficit Versus Petroleum*, Environmental Research Letters, 4 (2) [available online at http://dx.doi.org/10.1088/1748-9326/4/2/024001].

City of Portland Bureau of Planning and Sustainability, 2009, *Climate Action Plan 2009* [available online at http://www.portlandonline.com/bps/index.cfm?c=49989, accessed March 19, 2010].

Sahely H.R., Dudding S., and Kennedy C.A., 2003, *Estimating the Urban Metabolism of Canadian Cities: Greater Toronto Area Case Study*, Canadian Journal of Civil Engineering 30(2) 468-483 [available online at http://dx.doi.org/10.1139/l02-105].

Searchinger T, et al., 2008, *Use of U.S. Croplands for Biofuels Increase Greenhouse Gas Through Emissions from Land-Use Change*, Science 319(5867) 1238-1240 [available online at http://dx.doi.org/10.1126/science.1151861].

Society for Environmental Toxicology and Chemistry, 1993, *Guidelines for Life Cycle Assessment: A Code of Practice*. Pensacola, FL.

Stokes J and Horvath A, 2009, *Energy and Air Emission Effects of Water Supply*, Environmental Science and Technology 43(8) 2680-2687
[available online at http://dx.doi.org/10.1021/es801802h].

Suh S. et al., 2004, *System Boundary Selection in Life-Cycle Inventories Using Hybrid Approaches*, Environmental Science and Technology 38(3) 657-664
[available online at http://dx.doi.org/10.1021/es0263745].

Svidén J. and Jonsson A., 2001, *Urban Metabolism of Mercury Turnover, Emissions and Stock in Stockholm 1795–1995*, Water, Air, and Soil Pollution: Focus 1(3-4) 179-196 [available online at http://dx.doi.org/10.1023/A:1017512423006].

Tarr J.A., 2002, *The Metabolism of the Industrial City: The Case of Pittsburgh*, Journal of Urban History 28 511-545 [available online at http://dx.doi.org/10.1177/0096144202028005001].

Tillman A., Svingby M., and Lundström H., 1998, *Life Cycle Assessment of Municipal Waste Water Systems*, The International Journal of Life Cycle Assessment 3(3) 145-157 [available online at http://dx.doi.org/10.1007/BF02978823].

Warren-Rhodes K. and Koenig A., 2001, *Escalating Trends in the Urban Metabolism of Hong Kong: 1971-1997*, Ambio 30(7) 429-438 [available online at http://dx.doi.org/10.1579/0044-7447-30.7.429].

Western Climate Initiative, 2010 [information available online at http://www.westernclimateinitiative.org/].

Weidema B.P. and Wesnaes M.S., 1996, *Data Quality Management for Life Cycle Inventories – An Example of Using Data Quality Indicators*, Journal of Cleaner Production 4(3-4) 167-174 [available online at http://dx.doi.org/10.1016/S0959-6526(96)00043-1].

Wolman A., 1965, *The Metabolism of Cities*, Scientific American 213(3) 179-190.

Zhang Y., Yang Z., and Yu X., 2009, *Evaluation of Urban Metabolism Based on Emergy Synthesis: A Case Study for Beijing (China)*, Ecological Modelling 220(13-14) 1690-1696 [available online at http://dx.doi.org/10.1016/j.ecolmodel.2009.04.002].

Zhang Y. and Yang Z., 2007, *Eco-efficiency of Urban Material Metabolism: A Case Study in Shenzhen, China*, Acta Ecologica Sinica 27(8) 3124-3131 [available online at http://dx.doi.org/10.1016/S1872-2032(07)60067-5].